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REVIEW

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The effectiveness of sound-processing strategies on tonal language cochlear implant users: A systematic review

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Abstract

Importance: Contemporary cochlear implants (CIs) are well established as a technology for people with severe-to-profound sensorineural hearing loss, with their effectiveness having been widely reported. However, for tonal language CI recipients, speech perception remains a challenge: Conventional signal processing strategies have been demonstrated to possibly provide insufficient information to encode tonal cues, and CI recipients have exhibited considerable deficits in tone perception. Thus, some tonal language–oriented sound-processing strategies have been introduced. The effects of available tonal language–oriented strategies on tone perception are reviewed and evaluated in this study. The results may aid in designing and improving tonal language–appropriate sound-processing strategies for CI recipients.

Objective: The objective of this systematic review was to investigate the effects of tonal-language-oriented signal processing strategies on tone perception, music perception, word and sentence recognition.

Methods: To evaluate the effects of tonal language–oriented strategies on tone perception, we conducted a systematic review. We searched for relevant reports dated from January 1979 to July 2017 using PubMed, Cochrane Library, EBSCO, Web of Science, EMBASE, and 4 Chinese periodical databases (CBMdisc, CNKI, VIP, and Wanfang Data).

Results: According to our search strategy, 672 potentially eligible studies were retrieved from the databases, with 12 of these studies included in the final review after a 4-stage selection process. The majority of sound-processing strategies designed for tonal language were HiResolution® with Fidelity 120 (HiRes 120), fine structure processing, temporal fine structure (TFS), and C-tone. Generally, acute or short-term comparisons between the tonal language–oriented strategies and the conventional strategy did not reveal statistically significant differences in speech perception (or show a small improvement). However, a tendency toward improved tone perception and subjectively reported overall preferred sound quality was observed with the tonal language–oriented strategies.

Interpretation: Conventional signal processing strategies typically provided very limited F0 information via temporal envelopes delivered to the stimulating electrodes. In contrast, tonal language–oriented coding strategies attempted to present more spectral information and TFS cues required for tone perception. Thus, a tendency of improved performance in tonal language perception in CI users was shown.

KEYWORDS
cochlear implant, fine structure, strategy, tone

1 | BACKGROUND

The cochlear implant (CI) is a well-established technology for people with severe-to-profound sensorineural hearing loss. This technology bypasses damaged portions of the inner ear and uses electrical stimuli to deliver sound signals via a sound-processing strategy (sound-coding strategy) to the auditory nerve cells. The effectiveness of the CI technique has been widely reported.[1-3] These reports have shown that CI provides a fairly high level of speech perception in the majority of users, especially in quiet conditions. However, other reports have indicated that CI recipients exhibit considerable deficits in tone perception of native tonal language speakers, especially among prelingually deafened tonal language children.[4-13]

Sound-processing strategies are the core of CI technology, which transform speech into stimuli for the electrodes. Most sound-processing strategies have been designed based on the languages of Europe and the United States, which differ from tonal languages, that is, Sino-Tibetan, including Mandarin and Cantonese. Tonal language is widely used among people worldwide, with an estimated 1.3 billion people speaking tonal languages in the Asia-Pacific region.[14] In tonal languages, tone variations within the same phonemic segment produce a change in lexical meaning. Furthermore, tones are heavily loaded with semantic and grammatical information. Tones are essentially represented by fundamental frequency (F0). Tone perception is mainly based on 2 cues. The primary cue is F0 height and contour, while the secondary cue is supersegmental information (such as duration and amplitude) and the spectral envelope. The latter cue is especially important when F0 information is degraded, for example, in noise or other competition conditions.[10,14,15]

As mentioned previously, the design of the CI sound-processing strategy was mostly based on non–tonal language. The strategy typically provided very limited F0 information via temporal envelopes delivered to stimulating electrodes.

More recently, some studies have indicated that in clinically available coding strategies, such as Continuous Interleaved Sampling (CIS) and Advanced Combination Encoder (ACE), F0 information below 300 Hz is primarily encoded in the temporal pattern of electrical stimulation. These strategies extract only envelopes of the narrow-band signals and thus may not provide sufficient information to encode tonal cues. The CIS filters the input signal in a bank of band-pass filters and modulates high-rate pulse trains with the channel envelopes. During signal processing, the CIS presents pulses to each electrode in a nonoverlapping sequence. The key features of the CIS coding strategy include the following: (i) reducing channel interactions through the use of nonsimultaneous stimuli; and (ii) using a high stimulation rate on each channel (usually exceeding 800 p.p.s.), which enables tracking of rapid variations in speech, that is, most temporary cues that can be delivered by the CIS.[16] Because these features are critical for speech perception, the CIS is a standard and widely used coding strategy in CIs. However, the CIS delivers only little fine structure information and presents only envelope cues; that is, the CIS does not supply adequate information for perceiving tonal languages.

The envelope has been previously indicated to be important for speech perception, with fine structure being important for pitch perception, tone perception, and sound localization.[17,18] Under this condition, several studies have attempted to improve sound coding by combining the classical envelope and temporal coding. Such attempts have introduced modified or new sound-processing strategies that mainly focus on enhancing temporal fine structure (TFS), temporal periodicity cues to the fundamental frequency, or delivering more spectral information for better spectral resolution. Whether these strategies are effective and appropriate for tonal language CI recipients is a controversial issue. The objective of this study was to perform a systematic review to summarize the effects of the available tonal language–oriented strategies on tone perception. The results may aid in designing and improving tonal language–appropriate sound-processing strategies for CI recipients.

2 | METHODS

The present systematic review was implemented according to the Cochrane Handbook for Systematic Reviews of Interventions and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses.[19]

Criteria for considering studies eligible for this review were as follows: (i) participants—severe-to-profound hearing–impaired patients with CIs, where hearing impairment was the only disability; (ii) interventions—CI recipients who employed modified or newly developed tonal language–oriented sound-processing strategies; (iii) control group—CI recipients who employed conventional sound-processing strategies; and (iv) outcome measures—the primary outcome measures include performance of tone and speech perception, of which the latter includes vowel, consonant, monosyllable, disyllable, or sentence perception, and secondary outcome measures include performance on music perception or subjectively reported sound quality of overall preference of the tonal language–oriented strategies.

TABLE 1 Detailed search strategy

	Search query	Item found
#1	Cochlear Implants[MeSH]	8184
#2	Search ((((((pitch perception[MeSH Terms]) OR pitch discrimination[MeSH Terms]) OR music[MeSH Terms]) OR tone[MeSH Terms]) OR speech production[MeSH Terms]) AND cochlear implant[MeSH Terms])	672
#3	Search ((((((((pitch perception[MeSH Terms]) OR pitch discrimination[MeSH Terms]) OR music[MeSH Terms]) OR tone[MeSH Terms]) OR speech production[MeSH Terms]) AND cochlear implant[MeSH Terms])) AND strategy)	77
#4	((((((((pitch perception[MeSH Terms]) OR pitch discrimination[MeSH Terms]) OR music[MeSH Terms]) OR tone[MeSH Terms]) OR speech production[MeSH Terms]) AND cochlear implant[MeSH Terms])) AND coding strategy)	27

We searched several databases including PubMed, Cochrane Library, and 4 Chinese periodical databases (CBMdisc, CNKI, VIP, and Wanfang Data). Reports of clinical trials were also searched via ClinicalTrials.gov. We considered all relevant papers published during the period starting from January 1979 through to July 2017. During the search, no restrictions on language or publication status were applied.

The search strategy was oriented by a combination of Medical Subject Headings (MeSH) and keywords. The search terms for cochlear implant included Implants, Cochlear; Cochlear Implant; Implant, Cochlear; Cochlear Prosthesis; Cochlear Prostheses; Prostheses, Cochlear; Prosthesis, Cochlear; Auditory Prosthesis; Auditory Prostheses; and Prostheses, Auditory and Prosthesis, Auditory. The search terms for tone included Measurement, Speech Production; Measurements, Speech Production; Production Measurement, Speech; Production Measurements, Speech; and Speech Production Measurements. The search terms for pitch included Perception, Pitch; Perceptions, Pitch; Pitch Perceptions; Discrimination, Pitch; Discriminations, Pitch; and Pitch Discriminations. The search strategy is detailed in Table 1.

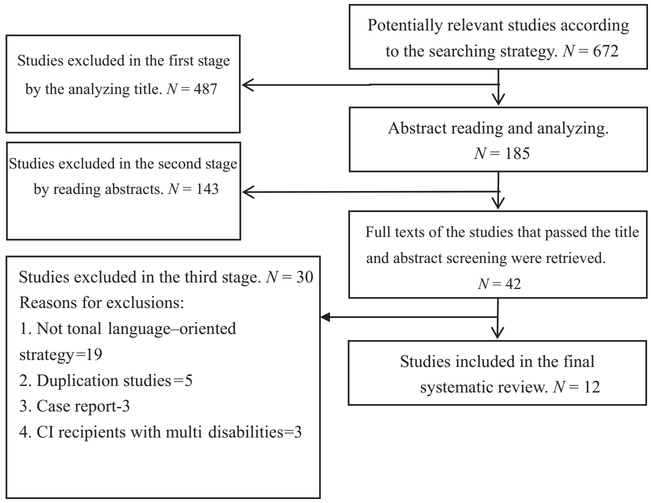

FIGURE 1 Strategy of studies selected and reasons for exclusion

3 | RESULTS

According to the inclusion criteria and search methods described above, 672 potentially eligible studies were retrieved from the database mentioned previously. We divided the selection of studies into 4 stages. For stage 1, a reviser selected eligible studies by analyzing the studies' titles. During this stage, 487 studies were eliminated. For stage 2, the reviser selected the studies by reading the abstracts to check whether the studies focused on tone perception of a tonal language–appropriate strategy in CI recipients. During this stage, 143 studies were eliminated. At stage 3, 42 full texts of studies that passed the title and abstract screening were retrieved and read in their entirety. During this stage, 30 studies were excluded. Reasons for exclusions were as follows: non–tonal-language-oriented strategy (19 studies), duplicated studies (5 studies), case report (3 studies), and CI recipients with multiple disabilities (3 studies). By stage 4, a total of 12 studies meeting the pre-established criteria were included in the final review.[8,14,20-29]

The bibliographic search strategy of studies selected and reasons for exclusion are shown in Figure 1. The detailed characteristics of the studies are summarized in Table 2. These 12 studies included in the final review were published during 2007 to 2017, and the study design included time series (6), before/after (3), and crossover (3). The investigated languages were Mandarin (8 studies) and Cantonese (3 studies), and 1 study compared music and speech perception between the fine structure processing (FSP) and the CIS in English. The majority of sound-processing strategies designed for tonal languages were HiResolution® with Fidelity 120 (HiRes 120), FSP, TFS, and C-tone. Of note, TFS is an experimental strategy, that is, not a commercially available strategy.

Several psychophysical studies have shown that simultaneous stimulation of 2 adjacent channels would create an additional pitch distinct from those elicited by stimulation of the 2 channels individually. Moreover, the new pitch could be varied systematically by adjusting the percentage of current presented to 2 channels.[30,31] Based on these phenomena, HiRes 120 was introduced by Advanced Bionics in 2006, which uses current steering to create virtual spectral channels through simultaneous stimulation of adjacent electrodes. Specifically, for each pair of adjacent electrodes, the percentage of current delivered to each electrode varies in 8 linear steps between 0% and 100%, thus potentially creating 8 different stimulation sites between the 2 electrodes. For the 16 electrodes of the Advanced Bionics CII and 90K devices, 120 virtual channels can be created. To match the 120 channels, narrow frequency analysis filters are used. Several research groups have compared tone perception performance between HiRes and HiRes 120.

Han et al[8] found that the mean tone perception scores at baseline (HiRes), 1-, 3-, and 6-month intervals (HiRes 120) were 74%, 75%, 75%, and 82% accurate, respectively. A 1-way ANOVA revealed no statistical differences across the 4 test intervals. However, the preference and rating questionnaire showed that parents of 3 of 18 children indicated that their children had no preference for either HiRes or HiRes 120, whereas the remaining 15 parents indicated that their children preferred HiRes 120 over HiRes. In a similar study, Lee et al[26] compared tone perception among Cantonese-speaking subjects, with results revealing that tone perception accuracy with HiRes and HiRes 120 was 77.5% and 77.6%, respectively. A paired-sample t test revealed no significant difference between the 2 coding strategies. The satisfaction ratings indicated that subjects preferred HiRes 120 over the HiRes strategy. Chang et al[25] found significantly improved Mandarin tone perception; specifically the mean scores from baseline with HiRes to 6 months with HiRes 120 were significantly different at 61.4% and 73.2%, respectively ($P = .006$). Furthermore, the questionnaire results indicated that all children preferred HiRes 120 to the conventional HiRes strategy.

The term "fine structure" was based on the work of the mathematician David Hilbert. According to Hilbert transform, any signal can be decomposed into a slowly varying envelope (ie, amplitude modulation) and a high-frequency carrier of constant amplitude to which he referred as the fine structure. For CI coding, the envelope is the main information carrier for speech (non–tonal language), while the fine structure is the main information carrier for music perception, sound localization, speech perception in noise, and tonal language perception.[17,18,32]

To overcome the limitation of envelope-based coding strategy, TFS and FSP were established. The FSP strategy makes use of FineHearing technology, aiming to improve both the temporal and tonotopic coding of sound. Through this technology, CI recipients may benefit from subtle pitch and timing details of the input by transmitting not only envelope cues but also rapidly changing pitch details. This strategy is based on channel-specific sampling sequences (CSSS), which are pulse packages triggered by every other zero crossing of the filter band outputs. The amplitude of these pulse sequences is scaled to the instantaneous amplitude of the Hilbert envelope.[33] The FSP particularly emphasizes temporal coding in several low-to-mid frequency bands. For the remaining channels, the FSP realizes tonotopic fine structure using virtual channels. That is, by shifting energy between 2 electrodes to a third location where no electrode exists, perception of a new pitch is created.[28,34]

Qi et al[22] compared the TFS and the CIS in a group of Mandarin-speaking CI recipients. While their study revealed no significant difference in performance between strategies in a speech test (MHINT, $P = .62$), the coding strategy had a significant effect on tone perception ($P < .01$). TFS improved tone perception by approximately 11 percentage points compared with the CIS strategy. Similar results have been obtained in other comparisons between the FSP/TFS and the CIS: Schatzer et al[24] found that mean tone perception was 59.2 ± 15.2% with CIS and 59.2 ± 15.3% with TFS, and sentence tests (CHINT) showed that mean score accuracy was 54.2 ± 27.7% with CIS and 55.9 ± 22.8% with TFS. In other studies, sentence test (MHINT) results and Mandarin tone perception scores have not been revealed to be significantly different between the FSP and the CIS; however, tone perception performance has exhibited a significant improvement with the FSP over time.[20,24]

Arnoldner et al[28] found that speech and music perception performance improved significantly after conversion from the CIS to FSP strategy. Specifically, in quiet conditions, mean accuracy on a number test rose from 78.39% to 85.00%, mean accuracy on a monosyllable test increased from 45.12% to 48.49%, and mean accuracy on the HSM sentence test rose from 57.97% to 69.25%. In noisy conditions, accuracy improved from 45.89% to 57.48% for the HSM sentence test at 15 dB S/N ratio, from 22.51% to 45.00% at 10 dB S/N ratio, and from 8.83% to 21.63% at 5 dB S/N ratio. Their study indicated that aside from envelope cues, the FSP strategy also delivers subtle pitch and timing differences of sound to the recipient to enhance speech perception in quiet and noisy conditions. In Chen et al's[21] study, speech perception and tone perception were tested preoperatively, at initial fitting, and at 3 and 6 months after first fitting. Results showed a significant improvement over time for speech perception (monosyllable in quiet conditions, $P = .014$; sentences in quiet conditions, $P = .007$; sentences in noisy conditions, $P = .039$) and tone perception ($P = .015$).

Given the limited access to F0 cues, a C-tone strategy with enhanced amplitude contour that covaries with F0 strategy was implemented. Ping et al[29] evaluated C-tone in a group of Mandarin-speaking postlingually deafened adults with CIs. Results showed that compared with the Advanced Peak Selection (APS) strategy, C-tone provided a small but significant improvement in tone, monosyllable, and disyllable perception: mean tone perception with C-tone with accuracies of 68.3%, 50.0%, 71.2%, and 78.1% for tones 1, 2, 3, and 4, respectively. Corresponding performances with APS were 62.5%, 47.3%, 63.5%, and 79.4%, respectively. Mean accuracy for monosyllables and disyllables with C-tone was 51.5% and 55.5%, respectively, while that with APS was 45.3% and 46.8%, respectively. Moreover, the majority of participants reported no deficit in quality with C-tone.

4 | DISCUSSION

This systematic review investigated the effects of tonal language–oriented signal processing strategies on tone perception, music perception, and word and sentence recognition in quiet and noisy conditions.

As mentioned earlier, the CIS strategy was introduced to avoid channel interaction through the use of interleaved nonsimultaneous stimuli at a high rate. Envelopes are extracted and compressed when the signal is passed through the digital filter bank, and then, the compressed envelopes modulate the biphasic current pulses, which are presented nonsimultaneously on multiple channels. This principle has been widely used in clinically available coding strategies, such as

TABLE 2 Characteristics of studies included in the systematic review

Study ID	Design	Investigated language	Target/control strategy	Principle of the new/modified strategy	Primary outcome measurement	Results	Conclusions
Arnoldner et al 2007	Time series	English	FSP/CIS	Delivering fine structure cues	Music and speech perception	The FSP improved speech perception, rhythm, and melody discrimination	Fine structure could offer a new quality of hearing with CIs
Wong et al 2008	Crossover	Cantonese	MEM/ACE/CIS	Enhanced temporal periodicity cues to F0	Speech perception in noise	Mean scores for the CIS were significantly worse than the MEM and ACE, while there was no statistically difference between the MEM and the ACE	The MEM retains similar segmental information provided by the ACE, and further optimizations of the MEM may lead to improvement in tonal language perception
Chang et al 2009	Time series	Mandarin	HiRes 120/HiRes	Delivering more spectral information	Tone perception	A statistically significant improvement from baseline with HiRes to 6 mons with HiRes 120 was found in tone perception	The study indicated a trend toward superior listening benefit with HiRes 120 compared with HiRes in Mandarin-speaking children
Han et al 2009	Time series	Mandarin	HiRes 120/HiRes	Delivering more spectral information	Tone perception	There was no significant difference in tone between 2 strategies. However, children preferred HiRes 120 significantly higher than HiRes.	HiRes 120 did not provide significantly improved lexical tone recognition compared to HiRes
Lee et al 2009	Time series (ABAB)	Cantonese	HiRes 120/HiRes	Delivering more spectral information	Tone perception	There was no significant difference in tone identification between 2 strategies. However, preference analysis showed that HiRes 120 significantly higher than HiRes.	HiRes 120 received a significantly higher rating for overall satisfaction
Schatzer et al 2010	Before/after	Cantonese	TFS/CIS	Delivering fine structure cues	Tone and speech perception	No statistically significant difference was found for the recognition of Cantonese lexical tones and sentences	Acute comparisons between the TFS and the CIS did not reveal any significant differences
Milczynski et al 2012	Before/after	Mandarin	F0mod/ACE	Enhanced temporal pitch cues	Tone and sentence perception	Significantly better lexical tone perception with the F0mod than with the ACE strategy	The F0mod led to significantly better lexical tone perception for the male voice, and enhanced temporal pitch cues may be relevant to tone recognition.
Qi et al 2012	Crossover	Mandarin	TFS/CIS	Enhanced temporal fine structure cues	Tone and speech perception	TFS improved tone perception by approximately 11 percentage points	TFS significantly improved tone perception
Chen et al 2013	Time series	Mandarin	FSP	Delivering fine structure cues	Speech and tone perception	There is a significant improvement in speech and tone perception over time	The FSP strategy improves speech and tone perception in Mandarin CI users

(Continues)

TABLE 2 (Continued)

Study ID	Design	Investigated language	Target/control strategy	Principle of the new/modified strategy	Primary outcome measurement	Results	Conclusions
Vandali et al 2016	Crossover	Mandarin	OPAL/ACE	Including additional processing to code F0 modulation in the stimulus envelope of each channel	Tone, sentence, and pitch perception	Compared with the ACE, lexical tone improved significantly in noise competition with the OPAL strategy	The OPAL can provide benefits to lexical tone perception in noisy conditions
Qi et al 2017	Time series	Mandarin	FSP/CIS	Delivering fine structure cues	Tone and speech perception, sound sensation test	For speech and tone recognition, there was no significant difference between the 2 strategies. However, tone recognition exhibited a significant improvement with the FSP strategy, and the subjects felt the FSP more "full" and "rich"	The FSP benefits tonal language users in tone perception
Ping et al 2017	Before/after	Mandarin	C-tone/APS	Enhanced amplitude contour (correlated with F0 contour)	Tone, monosyllable, disyllable perception	There is a small but significant improvement in tone, monosyllable, and disyllable perception after 2 wks of use with C-tone	C-tone provides a small but significant improvement for tone and speech perception in quiet conditions with no change in sound quality

Advanced Combination Encoders (ACEs), Spectral Peak, High Resolution, and CIS. Current CI coding strategies have effectively delivered envelope information to users, whereas fine structure information is represented very limitedly. That is, spectral information for perception of tonal languages is not delivered adequately.[10,28,35]

The mechanism of CI delivering spectral information mainly relies on the place of stimulation and rate of stimulation. The former is determined by which electrode is stimulated. Some pediatric CI users with prelingual severe-to-profound hearing loss have exhibited tremendous difficulties in perceiving and producing the Mandarin tone.[7,10,36] Evaluating tonal language perception could provide information about the efficiency of using place to deliver spectral information.

Han et al[8] reported that despite no statistical significance in tone recognition between HiRes 120 and HiRes, parents of most of the studied children showed a preference for the HiRes 120 strategy. Furthermore, approximately half of the participants showed improved tone recognition with the HiRes 120 strategy, which suggests that the children could possibly benefit from the increased spectral resolution offered by current steering. A similar result was also achieved in a Cantonese study.[26] An encouraging result was reported in Chang et al's[25] study, which indicated a significant improvement from baseline with HiRes to 6 months with HiRes 120 in tone perception, speech perception, and preference. Taken together, all of these studies showed a trend toward better tone perception and subjective preference for delivering more spectral information to the auditory nerve cells.

The CIS presents the envelope information, whereas the FSP presents both envelope and fine structure information simultaneously. The main difference is that CSSS is available in the latter, with which 2 low-frequency channels can be configured to code temporally the fine structure information.[37]

Most studies that have performed acute or short-term comparisons between the temporal fine structure–based strategies (such as TFS and FSP) and the widely used CIS strategy did not reveal differences in tone perception. However, a tendency toward a significant improvement with the TFS or FSP coding strategy was observed. Some reports confirmed that experienced users exhibited continuous improvement with the FSP strategy. Chen et al[21] reported that speech and tone perception performance improved significantly with the FSP strategy after 3 and 6 months of experience. These results indicate that even in experienced implant users, extended listening experience with the TFS or FSP may be required to make subtle fine structure cues potentially more accessible.[20-22,24] Chen and Zhang[38] reported that a zero crossing–based fine structure coding strategy might deliver Mandarin tone cues more effectively than the CIS, even at low signal-to-noise conditions. Kong and Zeng[39] evaluated in both the temporal and spectral domains the contributions of envelope and fine structure information to Mandarin tone perception in quiet and in noisy competition. Results indicated that in quiet conditions, normal-hearing subjects achieved nearly perfect tone perception with either spectral or temporal fine structure; however, with the envelope cue, accuracy reached only approximately 70%-80%. In addition, Kong and Zeng demonstrated that with the temporal envelope present only, 32 spectral bands were needed to achieve good performance in tone perception, but only 4 bands were required if with the additional temporal fine structure cues. Their results also showed that the envelope cues performed significantly lower in noise competition, which indicated the envelope cues were more susceptible in noise. The study also indicated that both spectral and temporal cues benefit tone perception, and furthermore, unlike speech perception, fine structure cues are more important than envelope cues for tone perception in both temporal and spectral domains, especially in noise conditions.[32] Given the upper limit of independent spectral channels available in contemporary CIs as imposed by channel interactions, the TFS coding strategy might be a better choice over spectral representations.[39]

Aside from the commercially available modified strategies described above, some studies have reported the effectiveness of experimental CI signal processing algorithms aimed at improving tone perceptions. Milczynski et al[23] investigated the effects of F0 modulation (F0 mod) on tone and sentence perception in Mandarin CI users. F0 modulation provides enhanced temporal envelope frequency cues by amplitude modulation of the multichannel electrical stimulation pattern at the F0 of the incoming speech signal. Results indicated that the F0 mod algorithm led to significantly better lexical tone perception for the male voice than the ACE strategy. A similar improvement was also found by Vandali and van Hosel[40,41] for the experimental algorithm named enhanced-envelope-encoder (eTone) over the conventional ACE coding strategy. In a later study, Vandali et al[14] compared the eTone, named “optimized pitch and language (OPAL),” with the ACE strategy. Their comparison demonstrated that the experimental OPAL strategy can improve tone perception in noise.

Vandali et al[42] developed an experimental strategy, multichannel envelope modulation (MEM), which enhances temporal periodicity cues to the F0. The MEM extracts the low-frequency (below 400 Hz) envelope of the broadband signal, which for voice/periodic signals contains F0 periodicity information, and uses this envelope to modulate the envelope of the band-pass-filtered channel signals derived from the ACEs. In this manner, F0 periodicity information in the broadband signal’s envelope is presented across all stimulation channels. Wong et al[27] compared the MEM with the ACEs and CIS in Cantonese-speaking CI recipients. They revealed that speech recognition performance with the CIS was significantly worse than that with the MEM and ACEs, with no statistical difference between the MEM and the ACEs. This result indicates that the MEM retains similar segmental information provided by the ACEs.

In summary, modified speech coding strategies have attempted to present more spectral information as well as temporal fine structure cues to CI users. Detailed spectral information and temporal fine structure cues have been demonstrated to be important for tone perception. Clinical data using modified coding strategies have produced somewhat mixed results, with a majority of studies showing a trend of modest improvement in tone perception performance in tone language–speaking individuals with CIs.

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CONFLICT OF INTEREST

We declare that we have no conflict of interest to this work.

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